Third Harmonic AC Susceptibility in Multifilamentary Wires

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AC magnetic field dependence of fundamental and third harmonic AC susceptibilities (χ_1'', χ_3' and χ_3'') were measured for two Nb-Ti multifilamentary wires with different filament diameters to investigate the effect of the reversible motion of fluxoids. The results agree approximately with the prediction of the Campbell model in which the reversible motion of fluxoids is treated. The critical current densities estimated from AC susceptibilities and that from the hysteresis of DC magnetization are compared. The large difference of the critical current density at high magnetic field from two methods seems to be explained by the distribution of the filament size.

INTRODUCTION

The measurement of third harmonic AC susceptibility has been used for characterization of oxide superconductors, such as the critical temperature, the irreversibility line and the critical current density[1, 2]. The Campbell model is used instead of the completely irreversible Bean model to estimate the critical current density from the observed AC susceptibility when the reversible fluxoid motion is remarkable. In oxide superconductors, the estimation is not easy because of particular characteristics such as large anisotropy, large thermal agitation, and existence of inter- and intra-granular currents, etc. On the other hand, these problems are little in conventional metallic superconductors. It is expected that the reversible fluxoid motion is remarkable in multifilamentary wires with filament diameter comparable to or smaller than the AC penetration depth.

In this paper, the effect of the reversible fluxoid motion on the third harmonic AC susceptibility is measured for Nb-Ti multifilamentary wires. The critical current density is analyzed using the result of the numerical calculation based on the Campbell model and the result is compared with the experimental result of DC magnetization hysteresis. Discussion is given for the reason for deviation of estimated values between the two methods.

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EXPERIMENTAL

Specimens investigated are Nb-47 wt%Ti multifilamentary wires with Cu matrix. The initial volume ratio of copper to Nb-Ti is about unity. After a repetition of combination of cold drawing and heat treatment at 400 ℃ for 80 hours for three times specimens were twisted. The specifications of the specimens are listed in Table 1.

The fundamental and the third harmonic AC susceptibilities were simultaneously measured using two two-phase lock-in amplifiers with a fundamental frequency, $f = 35.0$ Hz, and its third harmonics frequency, 105.0 Hz. The third harmonic frequency was generated by a simple PLL circuit from an input signal of the fundamental frequency. The measurement was carried out at varying AC magnetic field amplitude under fixed temperature and DC magnetic field for the purpose of estimating the critical current density. The DC and the superposed AC magnetic fields were applied up to 6 T and 0.03 T, respectively. The temperature was controlled in an atmosphere of He gas in the range of 4.2 K to T_c. The DC magnetization was measured by a SQUID magnetometer.

RESULTS AND DISCUSSION

Figure 1 shows the results of AC magnetic field dependence of χ_3'' for the two specimens. It is found that the peak value of χ_3'' decreases according to increasing the DC magnetic field. This result is explained from the magnetic field dependence of λ_0'. That is, λ_0' is expressed as

$$\lambda_0' = \left(\frac{H_0 d_i}{J_c}\right)^{1/2}, \tag{1}$$

where H_0 is the DC magnetic field, $d_i = a_f/4$ is the interaction distance expected in the present specimens with strong pinning centers and a_f is the fluxoid spacing. According to increasing DC magnetic field J_c decreases and λ_0' increases, resulting in more remarkable effect of reversible motion. It is also found that the decrease in the peak value of χ_3'' is small in the specimen with larger d_f, i.e, larger $d_f/2\lambda_0'$.

Here, we shall estimate the critical current density from the AC susceptibilities. According to the Campbell model, the amplitudes of AC magnetic field at the peaks of AC susceptibilities are determined uniquely by $d_f/2\lambda_0'$ and the penetration field, $H_p = 4J_c d_f/3\pi$. For example, in the case of negative peak of χ_3'', the relation is approximately given by

$$H_{mp\chi_3''}/H_p = 1.41[1 + 2(2\lambda_0'/d_f)^2]. \tag{2}$$

Table 1 Specifications of multifilamentary Nb-Ti specimens.

Specimen No.		1a	2
wire diameter	D_W(mm)	0.144	0.299
filament diameter	$d_f(\mu m)$	1.26	2.62
filament spacing	$d_N(\mu m)$	0.31	0.644
twist pitch	l_p (mm)	1.46	5.35
the number of filaments	N_f	4152	4152
critical temperature	T_c (K)	8.7	8.7

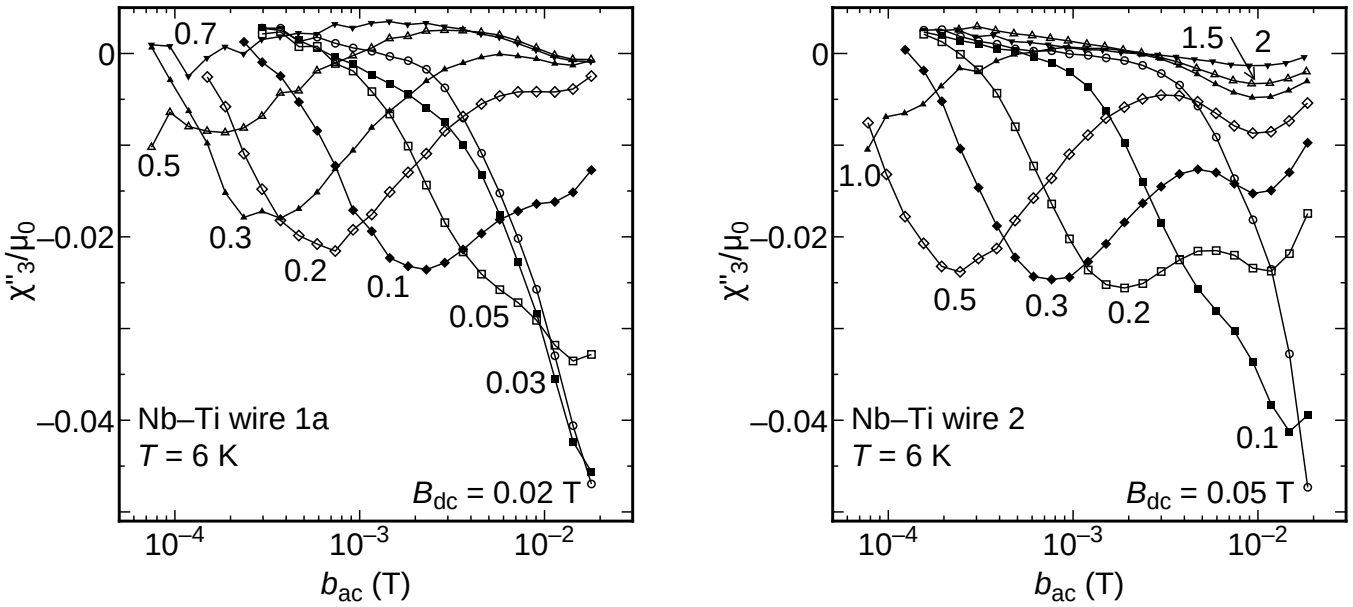

Figure 1 AC magnetic field dependence of χ_3'' in (a) specimen 1a and (b) specimen 2 at various DC magnetic fields at $T = 6.0$ K.

The corresponding peak value of χ_3'' is approximately expressed as,

$$-\chi_{3\mathrm{m}}'' = 0.05612/[1 + 5(2\lambda_0'/d_\mathrm{f})^2]. \tag{3}$$

Therefore, $d_\mathrm{f}/2\lambda_0'$ can be estimated using Eq. (3). Then, J_c can be estimated from Eq. (2). On the other hand, the value of J_c is also estimated from the hysteresis of DC major magnetization curve as $J_\mathrm{c} = 3\pi\Delta M/4d_\mathrm{f}$.

The results of J_c estimated from the various peaks of AC susceptibilities and DC magnetization hysteresis are shown in Fig. 2. Generally speaking, J_c's from AC susceptibilities are larger at low fields and smaller at high fields than J_c from DC magnetization hysteresis. In the beginning we shall compare the results from AC susceptibilities. Although the difference between the results from χ_1'' and χ_3'' is small, the difference between the results from χ_3' and χ_3'' tends to increase according to increasing magnetic field. This seems to be ascribed to the deviation from the Campbell model at high magnetic fields.

Secondly we shall compare the results from AC and DC measurements. The lower J_c's from AC measurements at high fields might be explained by the distribution of the filament size, while the filament size is assumed as constant in the present calculation. If the distribution of the filament size is taken into account, the effect of the reversible motion is suppressed by broadening the distribution of the filament size, since the magnetic flux is mainly determined by filaments with the larger size[2]. It means that J_c's from AC measurements are underestimated. It is to be noted that the reduction in J_c due to the distribution becomes less significant at low fields where $d_\mathrm{f}/2\lambda_0'$ is large and the phenomenon is more irreversible. Therefore, the magnetic field dependences estimated from the two methods seem to become close to each other by taking account of the distribution of the filament size. However, the reason for the larger J_c estimated from AC susceptibilities at low magnetic fields is still an open question.

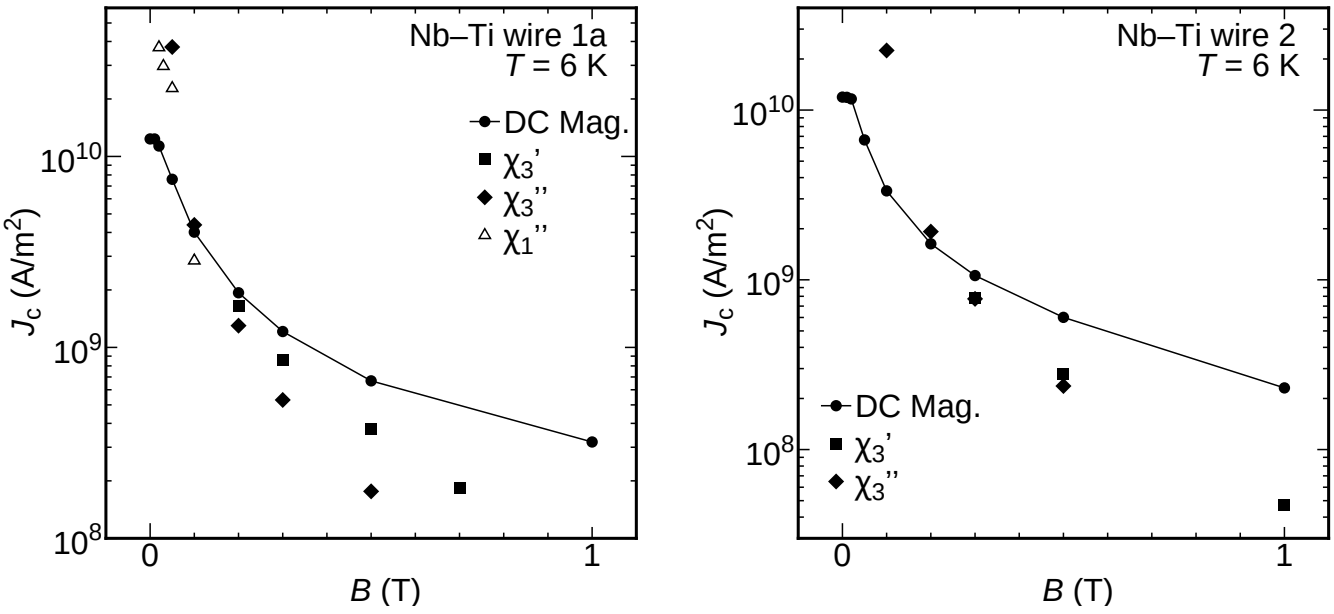

Figure 2 Critical current density estimated from the various peaks of AC susceptibilities and DC magnetization for (a) specimen 1a and (b) specimen 2 at $T = 6.0$ K

CONCLUSION

In this paper, the fundamental and third harmonic AC susceptibilities were measured for two Nb-Ti multifilamentary wires with different filament diameters and the following results are obtained. (1) The peak value of AC susceptibilities decreases monotonically according to increasing magnetic field. The decrease of the peak value of AC susceptibilities is small in the specimen with larger d_f. These are explained from the magnetic field dependence and difference of $d_\mathrm{f}/2\lambda_0'$. (2) The critical current density from the AC susceptibilities at high magnetic fields is underestimated due to the distribution of the filament size. However, the reason for the difference of J_c's from AC and DC measurements at low fields is not clear.

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